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AN INVESTIGATION OF UNSTEADY STALL PHENOMENON ON A SLENDER ELLIPTIC CYLINDER

Final Report

James C. Williams III

September 30, 1977

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13. ABSTRACT

An investigation has been conducted to determine the lift hysteresis loops on a slender elliptic cylinder undergoing small amplitude angle of attack oscillations about some mean angle of attack. The results obtained in this investigation are briefly reviewed in this final report. The investigation was conducted in three phases. In the first phase the boundary layer over the cylinder was assumed to be entirely laminar. Simple lift hysteresis loops are obtained in this case and these hysteresis loops exhibit some of the same general characteristics as the lift hysteresis loops for airfoils oscillating in pitch.

The second phase of the investigation involved a study of the rature unsteady boundary layer separation. Analytical solutions were obtained for the unsteady laminar boundary layer equations for several flows which approach separation. These solutions verify the Moore-Ratt-Sears model for unsteady boundary layer separation, at least for the case of upstream moving separation. It does not appear that solutions are possible for the case of downstream moving separation at this time.

In the final phase of this investigation an attempt was made to determine the lift hysteresis loops for the case where the boundary layer on the cylinder is partially turbulent. It was found that a solution to this problem, by the solution technique proposed, is not possible at this time.

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AN INVESTIGATION OF UNSTEADY STALL PHENOMENON ON A SLENDER ELLIPTIC CYLINDER

by

James C. Williams III

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INTRODUCTION

The present report is the final report on an investigation made to determine the unsteady lift hysteresis on a simple body, an elliptic cylinder, oscillating in a uniform stream. The purpose of the investigation was to provide some insight into the problem of lift hysteresis or dynamic stall which occurs on an airfoil oscillating about some mean angle of attack, in a uniform stream. This, in turn, is a simplification of the practical problem of dynamic stall encountered by a helicopter blade during each revolution of the rotor.

The investigation was supported by the U. S. Army Research Office under grants DA-ARO-D-31-124-72-G-134 and DA H CO4-75-G-0007, both entitled "An Investigation of Unsteady Stall Phenomenon on a Slender Elliptic Cylinder". The work on these grants was carried out during the period from March 15, 1972 through September 30, 1977.

This final report provides a brief statement of the problem investigated, and presents the results obtained and conclusions reached during each phase of the investigation, a list of reports and papers which resulted from the investigation and a list of the personnel who participated in the investigation.

STATEMENT OF THE PROBLEM

The purpose of the investigation was to determine the variation of lift with time for an elliptic cylinder which oscillates with an angle of attack amplitude $\Delta\alpha$, about some mean angle of attack, α_0, in a uniform stream of velocity U. The amplitude of the oscillations, $\Delta\alpha$, was assumed small, in which case the velocity at the upper edge of the boundary layer, u_δ, is given by:

$$\frac{u_\delta}{U} = \frac{1}{R}\{(1+\beta)\sin(\eta-\alpha_0) + \frac{\Gamma_0}{2\pi U\ell}\} +$$

$$\Delta\alpha\ \{\frac{1}{R}[\frac{\Gamma_{11}}{2\pi\ell U} - (1-\beta)\cos(\eta-\alpha_0)]\sin\omega t$$

$$+ \frac{1}{R}[\frac{\Gamma_{10}}{2\pi\ell U} - \omega\beta - \omega(\frac{1-\beta^2}{2})\cos 2\eta]\cos\omega t\} \tag{1}$$

Here $R = \sqrt{\sin^2\eta + \beta\cos^2\eta}$, β is the fineness ratio of the elliptic cylinder, η is a parametric angle related to the distance measured along the cylinder surface, x, by $dx/d\eta = -R/2$, ℓ is the length of the major axis of the ellipse, ω is the frequency of oscillation and t is time. The unsteady circulation is assumed to be given by

$$\Gamma(t) = \Gamma_0 + \Gamma_{10}\,\Delta\alpha\cos\omega t + \Gamma_{11}\,\Delta\alpha\sin\omega t\ .$$

The values of Γ_{10} and Γ_{11} must be determined so that the rate at which vorticity is shed into the wake is equal to the rate of change of the circulation about the cylinder. This criterion is given by:

$$\frac{d\Gamma}{dt} = \frac{1}{2}\bar{u}_\delta^{\,2} - \frac{1}{2}\underline{u}_\delta^{\,2} + \underline{u}_\delta\frac{d\underline{x}_s}{dt} - \bar{u}_\delta\frac{d\bar{x}_s}{dt} \tag{2}$$

where the upper and lower bars denote conditions at separation on the upper and lower surfaces of the body, respectively.

The problem then becomes one of determining the values of Γ_{10} and Γ_{11} which satisfy equation (2). To accomplish this, values of Γ_{10} and Γ_{11} are first assumed and the boundary layer development, over both the top and bottom surfaces of the elliptic cylinder, is calculated up to separation. Once the locations of the upper and lower separation points were determined, equation 2 can be used to determine if the proper values of Γ_{10} and Γ_{11} had been assumed. If the assumed values of Γ_{10} and Γ_{11} did not satisfy equation (2), new values were assumed and the process was repeated. An iteration scheme was set up so that one could rapidly converge on the proper values of Γ_{10} and Γ_{11}.

Initially the problem was formulated for the case where the boundary layer on the elliptic cylinder was laminar. A later phase of the investigation explored the case where the boundary layer was assumed to become turbulent at the points of minimum pressure.

It is clear from equation (2), that the unsteady lift characteristics depend upon the nature of the moving separation points on the body. The analysis discussed above it was assumed that the separation points were the points of vanishing shear on the upper and lower surfaces of the body. It is well known that this is not a correct assumption. For the case of small amplitude, low frequency oscillations, however, it is probably a reasonable assumption. Nevertheless, it was decided to investigate the nature of unsteady separation as part of this project in an effort to determine the proper manner in which equation (2) should be evaluated. An effort was made then, as part of this investigation, to determine the nature of unsteady laminar boundary layer separation.

RESULTS AND CONCLUSIONS

Laminar Boundary Layer Calculation - Oscillating Elliptic Cylinder

In the first phase of the investigation the calculations, indicated earlier, were carried out for the case where the boundary layer on the elliptic cylinder was assumed to be entirely laminar. The results for this case are presented in Reference 1.

The solution technique employed in the laminar boundary layer analysis was a momentum integral technique. From these calculations it was possible to determine the motion of the upper and lower separation points and the lift hysteresis loops for the oscillating cylinder.

The calculated lift hysteresis loop direction was found to change from counterclockwise to clockwise as the mean angle of attack was increased from two degrees to angles of attack within the steady state stall region. In addition, the hysteresis loops become larger in size at angles of attack corresponding to and beyond steady state stall. Both of these results are in general agreement with results obtained experimentally for lift hysteresis curves of airfoils oscillating in pitch.

The same calculations were carried out for the potential flow corresponding to a stationary elliptic cylinder with a free stream which oscillates in angle of attack. The results obtained in this case were compared with these obtained for the case of an oscillating cylinder. These calculations show that for these two cases the lift hysteresis loops were similar in structure but opposite in direction. At the angle of attack for which this calculation was carried out, the hysteresis loop for the oscillating body in a stationary stream was clockwise while the hysteresis loop for the stationary body in an oscillating stream was counterclockwise. The potential flows for the two systems differ only by a term proportional to the time rate of change of the angle of attack; a term which describes the influence on the potential flow of the added mass effect normally observed when a body is accelerated in unsteady flow. Additional results obtained in this phase of the investigation are presented in Reference 1.

The Nature of Unsteady Boundary Layer Separation

As has been pointed out earlier, the criterion which determines the unsteady circulation about the body, and thus the lift on the body, includes both the velocity at the boundary layer edge at separation and the location of separation (equation 2). In carrying out the calculations for the laminar boundary layer case, described above, separation was assumed to occur at the point of vanishing shear. It is well known that this is not correct but the error introduced by this assumption for small amplitude oscillations at low frequencies should be negligible. Nevertheless, it was decided to look closely at the problem of unsteady separation to determine whether or not it is possible to determine just what the criterion for separation in unsteady flow is. The results of this phase of the overall investigation are presented in References 2, 3 and 4.

In the first of these investigations it was shown that for a certain class of unsteady flows, namely those in which the velocity at the edge of the boundary layer is a linear function of x and t, the flow appears, in the appropriate moving coordinate system, as a steady flow over a wall moving at constant velocity. Solutions to the problem in this moving coordinate system are straightforward using well developed numerical solution techniques. These solutions, once obtained, can be transformed back into the fixed coordinate system, where the flow is unsteady, and used to infer the nature of unsteady boundary layer separation. Solutions were obtained for the case where the boundary layer edge velocity, in the moving coordinate system, decreased linearly with distance. The solutions obtained tended to verify the Moore-Rott-Sears model for unsteady separation in which unsteady separation is characterized by the simultaneous vanishing of the velocity and the shear, at a point with the boundary layer, as viewed in a coordinate system moving with separation. Solutions were only obtained for the case corresponding to upstream moving separation.

In References 3 and 4 more general problems were considered. It was shown that the method of semi-similar solutions was well suited for obtaining solutions to the unsteady boundary layer equations and that solutions obtained, using this method, for flows leading to separation could be used to infer the nature of unsteady separation. Reference 3 considered a flow which is an unsteady variation of Howarth's linearly retarded flow while Reference 4 considered an unsteady variation of the Falkner Skan flows. In each case the solutions verify the Moore-Rott-Sears model for unsteady boundary layer separation in the case where separation is moving forward along the body. It has not been possible as yet to obtain solutions for the case where separation moves backward along the body. Williams (Reference 5) has shown that in the case where the separation point is moving downstream the problem is still parabolic, but is not well posed. For this reason it has not been possible, as yet, to obtain solutions which indicate the nature of downstream moving separation.

The method of semi-similar solutions, which proved quite successful in determining the nature of unsteady, upstream moving separation, was extended to the problem of unsteady turbulent boundary layers in Reference 6. It was shown that the method could be applied to certain turbulent boundary layer flows. The question of unsteady turbulent boundary layer separation was not addressed, however, since it was felt that the algebraic representation for the eddy viscosity employed in Reference 6 was not realistic for flows which separate.

<u>Turbulent Boundary Layer Calculations - Oscillating Elliptic Cylinder</u>

In the third and final phase of this investigation an attempt was made to determine the lift hysteresis loops for the oscillating elliptic cylinder in the case where the boundary layer on the cylinder is partially turbulent. The potential flow, given by equation 1, may be written simply as

$$u_\delta(x,t) = u_{\delta_0}(x) + u_{\delta_1}(x)\,\Delta\alpha \cos \omega t + u_{\delta_2}(x)\,\Delta\alpha \sin \omega t. \tag{3}$$

The logical method of solution of the boundary layer equations in the case where the external velocity is of this form is to expand the solution in a series in the parameter $\Delta\alpha$. The first term in such a series is the steady state solution for the elliptic cylinder at the mean angle of attack, α_0. In order to determine the vorticity shed into the wake at separation, it is necessary to solve the equations for each term in the series up to the separation point. In the laminar case this is no problem for the momentum integral method passes through separation without any trouble. In the turbulent case, a number of different solution techniques were tried. The finite difference technique of Cebeci and Smith(7), and the integral methods of Nash and Hicks(8) and of White(9) all failed to predict a definite separation point for the steady state case (the first term in the series). Attempts were made to include an interaction effect in the calculation using the technique devised by Dancey and Pletcher(10), but this technique also failed to predict separation. Finally, the method of Nash and Hicks(8) was reformulated using the velocity profile given by Altstatt(11). It was felt that this velocity profile might eliminate the problems encountered because it does not contain a logarithmic singularity as the friction velocity, u_τ, approaches zero. It turns out, however, that this method also runs into difficulty as separation is approached and, therefore, cannot be used to predict separation.

Apparently the problem, in the case of turbulent momentum integral methods, results from the fact that the product of the boundary layer thickness, δ, and the friction velocity, u_τ, appears throughout the calculations. As separation is approached the friction velocity, u_τ, approaches zero but the boundary layer thickness becomes large. The product, therefore, behaves badly unless extreme care is used in the calculation.

In view of the above results it was concluded that the lift hysteresis loops could not be obtained at this time for the case where the boundary layer is turbulent. This problem deserves further attention.

PUBLICATIONS AND REPORTS

The following papers and reports, presenting portions of the work supported by the Army Research Office, under Grants DA-ARO-D-31-124-72-G134 and DAH-C04-G-0007, have been published in the open literature:

1. Williams, James C., III. "Large Amplitude, Low Frequency Solutions for a Certain Class of Laminar Boundary Layer Problems," AIAA Journal, Vol. 12, No. 3, pp. 265-266.
2. Williams, James C., III, and W. Donald Johnson. "Note on Unsteady Boundary Layer Separation," AIAA Journal, Vol. 12, No. 10, pp. 1427-1429.
3. Williams, James C., III, and W. Donald Johnson. "Semisimilar Solutions to Unsteady Boundary-Layer Flows Including Separation," AIAA Journal, Vol. 12 No. 10, pp. 1388-1293.
4. Williams, James C., III, and W. Donald Johnson. "New Solutions to the Unsteady Laminar Boundary Layer Equations Including the Approach to Unsteady Separation," In Unsteady Aerodynamics - Proceedings of a Symposium Held at the University of Arizona, March 18-20, 1975, Vol. I, pp. 261-282.
5. Williams, James C., III. "Semi-Similar Solutions to the Unsteady Turbulent Boundary Layer Equations," AIAA Paper No. 75-855, Paper Presented at the AIAA Eighth Fluid and Plasma Dynamics Conference, Hartford Connecticut, June 16-18, 1975.
6. Johnson, W. Donald, and James C. Williams III. "Lift Hysteresis of an Oscillating Slender Ellipse," Interim Technical Report, Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, N. C., September 30, 1977.

In addition to the above publications, the following two Ph.D. dissertations were written by personnel supported on the above grants.

1. "Unsteady Stall of a Slender Elliptic Cylinder in a Freestream of Sinusoidally Varying Angle of Incidence," Ph.D. Dissertation of Keith Lee Kushman, North Carolina State University, 1974.
2. "Unsteady Momentum Integral Analysis of the Laminar Boundary Layer on an Elliptic Cylinder Oscillating in Pitch," Ph.D. Dissertation of Walter Donald Johnson, North Carolina State University, 1974.

PARTICIPATING SCIENTIFIC PERSONNEL

One faculty member and three graduate students participated in the present investigation. Of the three participating graduate students, two received their Ph.D. degrees particularly as a result of the support provided by the investigation. The personnel who actively participated were:

Dr. James C. Williams III (Principle Investigator)

Dr. Walter Donald Johnson (Supported as a Graduate Research Assistant by these grants - Ph.D. received in August 1974)

Dr. Keith Lee Kushman (Supported as a Graduate Research Assistant by these grants - Ph.D. received in December 1974)

Mr. Chul Cho (Supported as a Graduate Research Assistant)

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